Fermi National Accelerator Laboratory

FERMILAB-Conf-93/333

Heavy Flavor Production at Fixed Target Photo- and Hadroproduction

S. Kwan

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

November 1993

Presented at the *Advanced Study Conference on Heavy Flavours*, Pavia, Italy, September 3-7, 1993

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

HEAVY FLAVOR PRODUCTION AT FIXED TARGET-PHOTO- AND HADROPRODUCTION

S. Kwan
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510, U.S.A.

ABSTRACT

Recent results on photo- and hadroproduction of heavy flavor particles from fixed target experiments at CERN and Fermilab are presented. These include results on production characteristics, cross-section and pair correlation for both charm and beauty mesons.

1. Introduction

After more than a decade of experimental studies of heavy flavor particles at various high energy laboratories, the subject of production of heavy flavor particles has entered into a new era as high statistics samples are now available. Production is interesting since it provides a meaningful test of perturbative QCD when the mass of the heavy quark is sufficiently high. Understanding heavy quark production is also necessary to predict the production rate for new particles and evaluate the background in many rare processes.

In QCD the lowest order processes are photon-gluon fusion for photoproduction [$O(\alpha_s\alpha_{em})$], and gluon-gluon fusion and quark-antiquark annihilation for hadroproduction [$O(\alpha_s^2)$]. In the last few years, there has been a major breakthrough in the theoretical front in that the next-to-leading order (NLO) calculations [$O(\alpha_s^2\,\alpha_{em})$ and $O(\alpha_s{}^3)$ respectively for photo- and hadroproduction] have been completed.[1-5] The results of these calculations indicate that the calculated cross sections are larger, by about 30% for photoproduction of charm and by about a factor of three for hadroproduction. Lowest-order calculations required a low value for the charm quark mass (around 1.2 GeV) to account for the magnitude of the cross section. Calculations including the higher order terms can describe (with a theoretical uncertainty of about a factor of three to four) the data with the more reasonable mass for the charm quark m_c of 1.5 GeV. The distributions in Feynman-x (x_f) and transverse momentum (p_t) are not significantly affected by the inclusion of higher order terms. There is, however, a small difference between heavy quark and antiquark production at high x_f which is not present in the lowest order calculations.

2. Experimental Techniques

Production studies are obviously an exclusive domain of hadron machines and both the CERN SPS and FNAL Tevatron have an extensive program devoted to these studies. While hadron machines have superior luminosity compared to e^+e^- colliders and hence heavy flavor particles are produced abundantly, the production rate of heavy flavor particles is small. In fixed target experiments at present machines, the ratio of the charm production cross section to the total inelastic cross section is 1/200 in photoproduction and 1/1000 in hadroproduction. The beauty cross section is estimated to be about another three orders of magnitudes smaller. The lifetimes of heavy flavor particles are short (from about 0.2ps for Λ_c to about 1 ps for D^+ and 1.5 ps for B mesons) and hence the typical decay length is of the order of a few mm. Furthermore, any particular decay mode of these particles has only a very small branching fraction and this makes collection of high statistics very difficult.

Earlier experiments in the late 70's to the early 80's searched for the heavy flavor particles by looking for bumps in the combinatorial mass spectra. Over the years, more sophisticated methods have since been developed. The real breakthrough was the successful introduction of silicon microstrip detectors (SMD) which were pioneered by the ACCMOR collaboration at CERN (experiment NA11) in 1982.[6] These detectors have good spatial resolution and unlike optical devices such as emulsion and bubble chambers, they can be implemented in all electronics experiments, thus making the collection of a high statistics sample possible. Using SMD, a photoproduction experiment at Fermilab, E691 reconstructed about 10K charm candidates in 1985, proving that fixed target experiments could be very competitive with e^+e^- colliders, even in decay studies of charm particles. The present generation of experiments like E687 have reconstructed about 80K charm events. The essential ingredients for a fixed target heavy flavor experiments are: 1) high resolution vertex detectors to measure the finite decay paths of these particles; 2) a large acceptance spectrometer with good momentum resolution and particle identification; 3) a selective and efficient trigger scheme; 4) a fast data-acquisition system and/or fast off-line filters and 5) massive computing farms to speed up the data crunching.

3. Inclusive Photoproduction Studies of Charm

Recent data on photoproduction of charm come from E691 [7], NA14' [8] and E687 [9] which collectively span the photon energy range between 50 GeV up to just above 300 GeV. A comparison of the NLO QCD calculation with the measured charm photoproduction cross-section is shown in Fig. 1. An adequate description of the data is achieved by using a value of 1.5 GeV for m_c. The x_f distributions of the D mesons measured in the three experiments are in agreement with each other and are shown in Fig. 2. These distributions peak at a value of x_f about 0.2 which is lower than the average x_f of 0.5 expected for charmed quarks produced via photon-gluon process. Fragmentation effects are therefore important. E691 has fitted the p_t^2 distribution to the form $d\sigma/dp_t^2 = A \exp(-b\, p_t^2 - c\, p_t^4)$ and found a value of b=1.07±0.05, c=-0.04±0.01, giving for the D mesons a mean p_t^2 of 1.16±0.04 GeV^2. The measurements by the E687 and NA14' collaborations are qualitatively similar. Using the same form, the E687 fit gives the values b=0.85±0.02, c= -0.03±0.01, giving a mean p_t^2 of 1.51±0.02 GeV^2. The higher mean p_t^2 of the D mesons measured by E687 is probably due to the higher beam energy they used.

Both E691 and NA14' have performed fits of their inclusive D mesons distributions in order to measure parameters of the photon-gluon fusion model. Using variants of the Lund string fragmentation model, E691 obtained a value of m_c = $1.74^{+.13}_{-.18}$ by fitting their p_t^2 and xf distribution and the total inclusive charm cross section as a function of photon energy. NA14', by fitting their p_t^2 distribution, have derived a value of 1.58±0.07 (statistical error only) for m_c.

NA14' reported a sample of 22 fully reconstructed double charm events [10] and recently, E687 [11] presented results from 325 fully reconstructed charm pairs. They also demonstrated that it is possible to study charm pair correlations using the soft π from the $D^{*+} \to D^0 \pi^+$ decay. Compared to the fully reconstructed charm pair sample, the statistical sample size that they obtained by using this kinematic tagging technique is increased by more than a factor of 10 and correlations can be studied over a much larger kinematic range because of the increased acceptance. Both NA14' and E687 show that the data is in good agreement with the photon-gluon process and the Lund fragmentation model predictions for the rapidity difference and invariant mass. However, significant disagreement between data and model predictions is observed in the azimuthal distribution and p_t of the charm pairs.

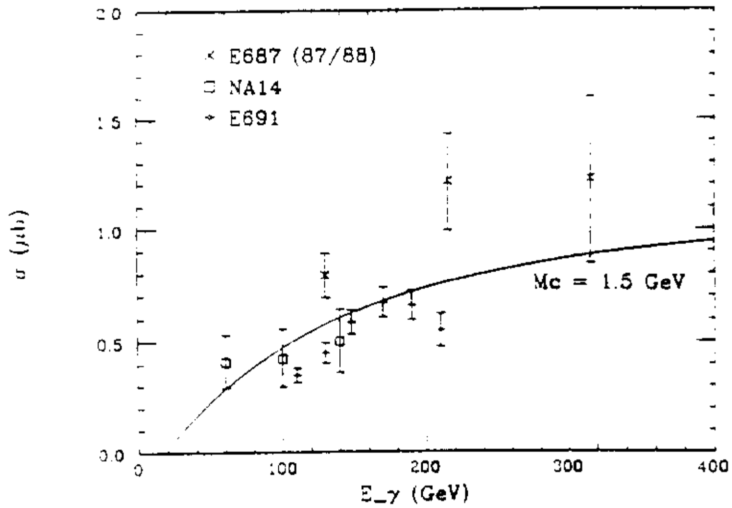

Fig. 1: The total cross section for the photoproduction of a pair of charmed quarks versus photon energy (E_γ) from the three photoproduction experiments. The curve shown represents the NLO calculation for m_c=1.5 GeV.

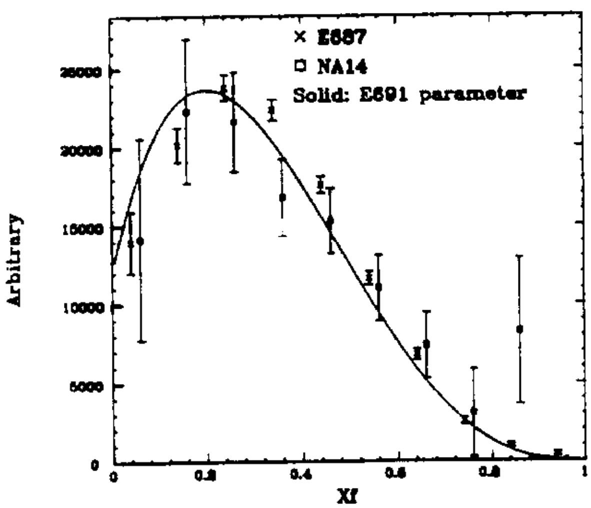

Fig. 2: The xf-dependence of D mesons

4. Hadroproduction of Charm

Hadroproduction is more difficult both theoretically and experimentally compared with photoproduction. The charm quark mass may be too light for the reliable application of perturbative QCD and the theoretical uncertainties are large and hard to estimate. Moreover, hadronization effects are important and are non-perturbative. Experimentally, besides the smaller production ratio and the higher multiplicity, there are a few open issues making comparison of different results very confusing. In the past, experiments had only limited statistics, typically in a limited number of decay modes. The problem is further compounded by the fact that different incoming beam particles and different target materials have been used. Thus, to get a clear picture, one needs to understand the following: 1) dependence on the atomic number of the target; 2) dependence on the incident particle type and 3) leading particle effects. By leading particle effect, we mean forward production of charm particles which have one or more valence quarks in common with those of the incoming projectile.

During the last couple of years, results from a few high statistics charm hadroproduction experiments have become available. The differential cross section is usually parametrized as $(d^2\sigma / dx_f\, dp_t^2) = (1-x_f)^n \exp(-bp_t^2)$ and the value of n and b are measured to determine the differential cross section. Fig. 3 summarizes the results on x_f dependence of recent experiments.[12]-[16] What is interesting is that the value of n measured for charmed mesons is similar but slightly less than the theoretical prediction for charm quarks. This hardening of the x_f distribution during the hadronization process can be explained by a model which includes the effects of the dragging of charm quarks produced at large rapidities in the color field of the beam fragments resulting in transfer of part of the momentum of these fragments to the charmed hadrons [5]. There seems to be a weak dependence on the beam energy in agreement with NLO QCD calculations which predict somewhat softer x_f distributions as the beam energy goes up.

With high statistics, no large leading particle effect has been observed. A bubble chamber experiment, NA27 [15], reported a large difference of 6.1±1.5 in the value of n between leading and non-leading D mesons based on 57 events. Both NA32[12] and E769[14] found that the leading particles are produced slightly more forward than the non-leading ones but the overall difference integrated over xf>0.0 is small. However, recently both WA82[17] and E769 have studied the differences between the numbers (N) of leading and non-leading charmed mesons in each bin of x_f. The asymmetry A, defined as difference between N(leading) and N(non-leading) over the sum of the two shows that the asymmetry increases from about 0 near x_f=0 to about 0.5 at x_f =0.65 (Fig 4). Clearly the data show much larger values of A than the small value predicted at high x_f for charm quarks using perturbative QCD. One the other hand, the Lund string fragmentation model incorporated in the Pythia Monte-Carlo program, while qualitatively reproduces the trend, predicts too large a value for A. Although the leading effect is significant at high x_f, because the differential cross-section falls off rapidly with x_f, the total asymmetry integrated over x_f >0 is small.

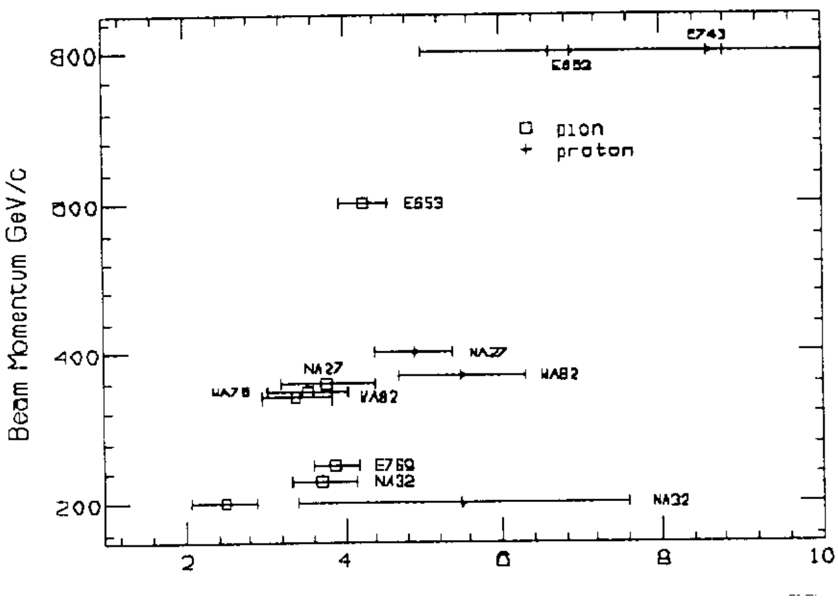

Fig.3: Value of n measured by different charm hadroproduction experiments

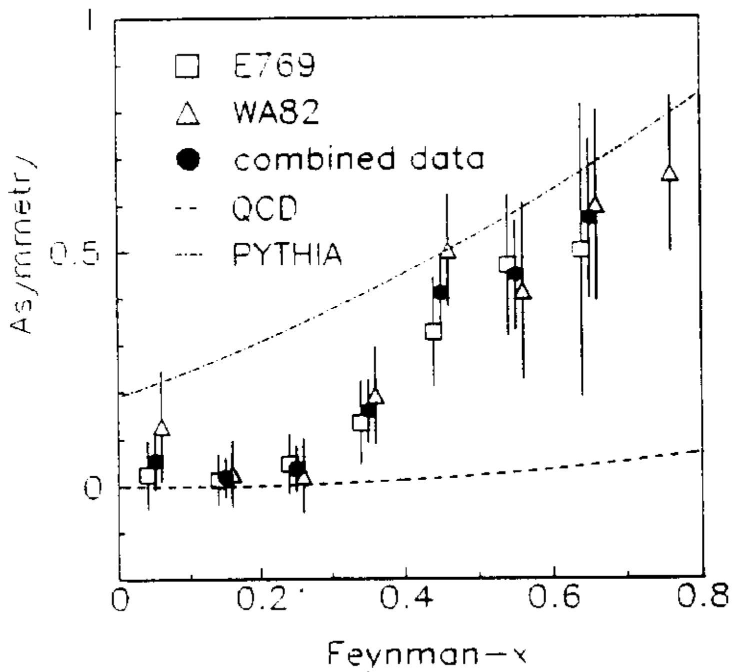

Fig. 4: Asymmetry versus xf. The dashed curve is based on the NLO QCD calculation for charmed quark production. The dot-dashed curve is the prediction from Pythia.

The p_t dependence seems fairly uniform across the range of incoming beam energies and incident particle type with a value of b close to 1. Recent high statistics experiments E769 and WA82 both observed that there is an excess of events at high p_t and that a better fit to the distributions at $p_t > 0.8$ GeV is obtained with $d\sigma/dp_t \propto \exp(-b'p_t)$.

New results on correlation are available from E653, WA75 and NA32.[18]-[21] There is good agreement between different experiments on the invariant mass of the pair $\langle m \rangle$, on the rapidity gap $\langle \Delta y \rangle$ and on the p_t^2 of the pair. When compared with theoretical predictions, while $\langle \Delta y \rangle$ is not very different, the measured values for $\langle m \rangle$ and $\langle p_t^2 \rangle$ are definitely larger than the theoretical predictions. The big discrepancy between the data and theoretical prediction, however, is in the azimuthal distribution $\Delta\phi$. NA32 has 557 charm pairs and WA75 has 177 pairs. Both experiments show a $\Delta\phi$ distribution which is significantly broader than the NLO predictions which yield a very prominent peak at $\Delta\phi$ close to 180°. This smearing is much more so than in the case of photoproduction and this may be explained by the fact that in hadroproduction, charm is dominantly produced by the gluon-gluon fusion process and there are effects from the intrinsic p_t of both incident gluons.

Fig. 5 summarizes the recent results on the production cross section from a π^- beam. Within large uncertainties, NLO QCD calculation predicts a cross-section which is consistent with the data.

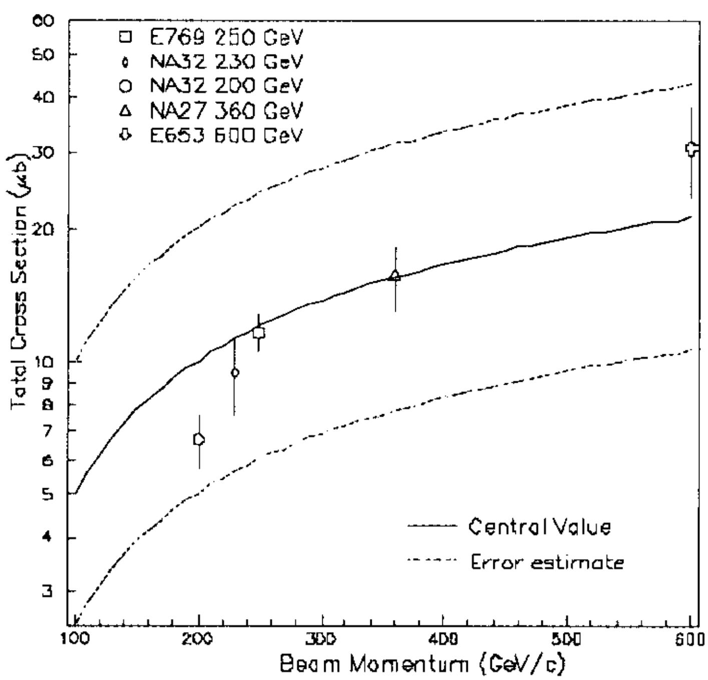

Fig. 5: Recent measurements of total charm cross-section in π beam and theoretical predictions.

4. Hadroproduction of Beauty

Despite the fact that beauty hadroproduction is a better test of QCD calculations, the smallness of the b cross-section at present fixed target energies, the complicated event topology and the consequent difficulties in extracting the signal explain why few experimental results have been obtained so far. Recently, two experiments at Fermilab have completed their analyses and presented results.

E653 [22] used a 600 GeV π^- beam in an emulsion target followed by a multiparticle spectrometer with SMD and a muon trigger. B particles are identified in the emulsion by decay topologies. Based on 9 beauty hadron pairs, they measured a pair cross-section for all xf, assuming linear A dependence, of 33±11±6 nb/nucleon. This is consistent with NLO QCD expectations. Fits of the inclusive single-hadron production distributions to the form $d\sigma/dx_f \propto (1-|x_f-x_0|)^n$ and $d\sigma/dp_t^2 \propto \exp(-bp_t^2)$ give $n=5.0^{+2.7+1.7}_{-2.1-1.7}$, $x_0=0.06^{+0.06+0.02}_{-0.07-0.03}$ and $b=0.13^{+0.05+0.02}_{-0.04-0.02}$ $(\mathrm{GeV}/c)^{-2}$. While the value of n is similar to charm at this energy with a positive offset, the inclusive p_t^2 distribution is much broader than for charm which is expected theoretically because of the larger mass of the b quark. The pairs tend strongly to be produced back-to-back, with an average pair p_t^2 which is nonzero, but smaller than the average inclusive p_t^2 for a single B particle. This result is consistent with NLO predictions.

With a 530 GeV π^- beam, E672 [23] used their di-muon spectrometer and the E706 multiparticle spectrometer and SMD to search for events with a J/Ψ decaying into $\mu^+\mu^-$ downstream of the primary interaction point. By demanding that the J/Ψ decay occur outside of the target material, they measured a total cross-section for b production of $43\pm13^{+16}_{-13}$ nb/nucleon based on 9±3 events.

5. Summary

The experimental photoproduction cross-sections, x_f and p_t^2 distributions are reasonably well described by the NLO QCD calculations after including the structure function and fragmentation effects. Fits of the inclusive D sample give a charm quark mass between 1.5 to 1.8 GeV which is in good agreement with the ones obtained from potential models and QCD sum rules. New data on photoproduced $D\bar{D}$ correlations from E687 and NA14' show that the rapidity difference and invariant mass is in good agreement with the Lund/Pythia predictions. However, there is small smearing in the azimuthal distributions when compared with theory but the smearing is not as much as that observed in the charm hadroproduction experiments.

A new photoproduction experiment E831 has been approved at Fermilab which will aim to collect 10X the statistics of E687.

In hadroproduction of charm, the new results are consistent with one another. The recent high statistics experiments find that the overall leading particle effect is small. The measured value of n for charm particles is similar to the theoretical prediction for charm quarks, and hadronization effects such as color drag are important to understand the result. There is strong evidence that there is enhanced leading charm particle production with increasing x_f which cannot be described by NLO QCD calculation for the production of charm quarks. Again, this effect may be explained by the hadronization process or by some other production mechanism. The difference between the prediction and experimental result is most striking in the azimuthal distribution of charm pairs in which rather than a peaked back-to-back distribution as predicted, experiments observed a much flatter distribution. Theoretical models could accommodate this by giving, without sound justification, an uncomfortably large intrinsic p_t to the incident partons. New results are expected in the coming year from experiments E791 which projects 200K fully reconstructed charm events (500 GeV π^- beam), WA89 which would settle, hopefully, the question of a large forward component in hadroproduction (340 GeV Σ^- beam) and from WA92 (350 GeV π^-) which, by virtue of the power of their vertex telescope, would contribute significantly to pair correlation studies.

In hadroproduction of beauty, after years of work, two experiments (E653 and E672) have presented results on production. So far, based on a small sample of events, the production characteristics are in reasonable agreement with theory. New results are expected from WA92 at CERN, E771 and E789 at Fermilab. All three experiments have reported the observation of clean B candidates.

6. Acknowledgments

I would like to thank my colleagues from ACCMOR and the E769/791 collaborations for frequent and stimulating discussions over the years. I am also indebted to P. Garbincius, D. Kaplan, S. Paul, L. Rossi and J. Wiss for their information and fruitful discussions.

7. References

1. P. Nason, S. Dawson and R.K. Ellis, Nucl. Phys. **B303** (1988) 607.
2. R.K. Ellis and P. Nason, Nucl. Phys. **B312** (1989) 551.
3. P. Nason, S. Dawson and R.K. Ellis, Nucl. Phys. **B327** (1989) 49.
4. W. Beenakker et al. Nucl. Phys. **B351** (1991) 507.
5. M. Mangano, P. Nason and G. Ridolfi, IFUP-TH-37/92.
6. E. Belau et al., NIM **214** (1983) 253.

7. E691, J.C. Anjos et. al., Phys. Rev. Lett. **62** (1989) p513.
8. NA14', M.P. Alvarez et al., CERN-PPE/92-28.
9. Jim Wiss, talk given at Phy. in Collison, Heidelberg, June 1993.
10. NA14', M.P. Alvarez et al., Phy. Lett. **B278** (1992) 385.
11. E687, P.L. Frabetti et al., Fermilab-PUB-93-072-E (1993).
12. NA32, S. Barlag et al., Z. Phys. **C49** (1991) 555.
13. E653, K. Kodama et al., Phy. Lett. **B284** (1992) 461.
14. E769, G.A. Alves et al., Phy. Rev. Lett., **69** (1992) 3147.
15. NA27, M. Aguilar-Benitez et al., Phys. Lett. **161B** (1985) 400.
16. E653, K. Kodama et al., Phy. Lett **B263** (1991) 573.
17. WA82, M. Adamovich et al., Phy. Lett. **B305** (1993) 402.
18. NA32, S. Barlag et al., Phy. Lett. **B247** (1990) 113.
19. NA32, S. Barlag et al., Phy. Lett. **B302** (1993) 112.
20. WA75, S. Aoki et al., Phy. Lett. **B209** (1988) 213.
21. E653, K. Kodama et al., Phy. Lett. **B263** (1991) 579.
22. E653, K. Kodama et al., Phy. Lett. **B303** (1993) 359.
23. E672, L. Dauwe et al., Proc. of the DPF92, World Scientific, (1993), 759.